

Project 1

Assigned February 19, 2008

Parts 1 and 2 due March 4, 2008

Part 3 due March 6, 2008

Assume a spherical atmosphere, us76.dat, us76.spline

1. Construct a layered atmosphere up to 50 km, with 5 km layers: Using the Curtis-Godson approximation¹ find the best representative pressure, P_{eff} , for each layer and set the layer temperature² and height $(T_{\text{eff}}, Z_{\text{eff}})^2$ to the corresponding values from the US76 atmosphere.

2. Nadir geometry: For the following conditions:

- wavelengths of 350 and 1000 nm
- albedos of 0.02, 0.2, and 1.0: Lambertian
- apparent solar zenith angles of 0, 45, and 80 degrees
- satellite viewing angle of 0 degrees
- Rayleigh single scattering as both a source and an extinction term

(a) Calculate and plot the refractive path through the atmosphere (applying Snell's law³ at the layer boundaries). Use spherical or plane-parallel atmosphere, your choice.

(b) Go to the plane-parallel approximation, and look at the three lowest layers (the "troposphere"). Considering the Rayleigh scattering⁴ as a loss to I_0 and a source term, from scattering, in each (of the three) layers, determine the upwelling radiation at the satellite viewing angle as a fraction of I_0 and plot the contribution seen by each layer to the total. (In other words, what fraction of the light exiting the atmosphere has seen each layer?) Ignore refraction in this part, but include the Rayleigh source from scattering upwelling radiation into the viewing geometry. Ignore polarization induced by Rayleigh scattering (by the way, solar radiation is highly non-polarized).

3. Limb scattering: For the following conditions:

- spherical atmosphere from (1)
- wavelengths of 350 and 1000 nm
- albedo = 0.1, Lambertian
- solar zenith angles of 0 and 45 degrees
- solar azimuth angle of 45 degrees (here I mean the azimuth angle with respect to the sun and the measurer, not the astronomical solar azimuth angle)
- Rayleigh single scattering as both a source and an extinction term
- ignore refraction

(a) Calculate and plot the radiation at the satellite as a fraction of I_0 for viewing tangent to each effective height. Treat the sun as a source of parallel rays and then consider the terms for scattering of incoming light, Lambertian reflection at the surface and a second scattering along the lines-of-sight. The second scattering terms may be approximated as

scattering from the same physical conditions (P_{eff} , T_{eff} , Z_{eff}) but with geometric factors appropriate to the problem.

(b) For measuring tangent to 30 km, and considering the sphericity of the atmosphere (but not refraction), what is the effective tangent height, in terms of column density of molecules along the path for the 30-35 km layer?

¹The Curtis-Godson approximation states that the effective pressure is given by

$$\bar{P} = \frac{\int P \rho dz}{\int \rho dz}, \text{ where } \rho \text{ is the density (for the effective pressure of a species with}$$

fractional concentration c , it is given by $\bar{P} = \frac{\int P c \rho dz}{\int c \rho dz}$). It is exact for Lorentz (*i.e.*,

pressure) broadened absorption or emission lines in the limits of very strong and very weak, and deviates in between. See Houghton, Section 4.4, and problem 4.13 for details.

²For temperature interpolation, you may wish to use a cubic spline interpolation, in order to gain experience with it. See cspline.f90 on the website. Otherwise, linear interpolation is fine.

³Index of refraction, Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$, where the angles are perpendicular to the interface. For the index of refraction at 288.15 K and 1013.25 millibar (mb) use:

$$(n - 1) \times 10^8 = 8060.77 + \frac{2481070.}{132.274 - \lambda^{-2}} + \frac{17456.3}{39.32957 - \lambda^{-2}}, \text{ where } \lambda \text{ is the wavelength in}$$

micrometers (microns, μm), and scale $(n - 1)$ as density, $\propto P/T$: This is equation 21 of Bodhaine, B.A., N.B. Wood, E.G. Dutton, and J.R. Slusser, On Rayleigh optical depth calculations, *J. Atmos. Ocean. Tech.* **16**, 1854-1861, 1999. (on website)

⁴Rayleigh scattering is given by (Bodhaine, equation 29):

$$Q_R \times 10^{28} = \frac{1.0455996 - 341.29061\lambda^{-2} - 0.90230850\lambda^2}{1 + 0.0027059889\lambda^{-2} - 85.968563\lambda^2}, \text{ where } \lambda \text{ is the wavelength in}$$

μm , and Q is in cm^2 (to be multiplied by the column density in cm^{-2} to determine the fraction of light scattered out of the beam). The scattering phase function is

$$\Phi = \frac{3}{4}(1 + \cos^2 \theta), \text{ normalized to } \int \Phi d\Omega = 4\pi.$$

Project 2

Assigned April 1, 2008 due April 22, 2006

This project consists of calculation of realistic atmospheric spectra for several measurement geometries. Ignore refraction in all calculations.

1. Infrared solar absorption spectrum for HCl R1 lines at 2923.732 cm^{-1} (H^{37}Cl) and 2925.897 cm^{-1} (H^{35}Cl). Using the plane-parallel atmosphere from before, calculate

pure absorption spectra for SZA of 45° for a spectral region covering these lines. Spectral resolution should be several times smaller than the Doppler line width. Line shapes are Voigt (**voigt363.f90**). Species included are HCl, H₂O, O₃, CH₄, and NO₂. Plot the result and then convolve with a typical instrument line width of 0.01 cm^{-1} (use a Gaussian of 0.01 cm^{-1} HW1/e, either using **voigt363.f90** or **gauss.f90**) and re-plot.

2. OH limb emission in far infrared. Calculate limb spectrum through entire atmosphere for tangent heights of 25, 30, 35, 40, 45 km. Spectral region $118\text{-}119 \text{ cm}^{-1}$. Spectral resolution 0.0002 cm^{-1} (approximately the Doppler width). Plot the result and then convolve with a typical instrument line width of 0.004 cm^{-1} (use a Gaussian of 0.004 cm^{-1} HW1/e) and re-plot. Use geometric paths and P_{eff} and T_{eff} values from Project 1.
3. Satellite back-scattered radiation: Calculate the ratio I/I_0 for absorption of sunlight by ozone, 300-330 nm. Using the plane-parallel atmosphere from before, calculate pure absorption spectra for SZA of 45° , viewing angle of 0° , albedo = 0.1. Use wavelength grid of cross sections. Plot results. Then, add Rayleigh scattering as loss and source terms, re-calculate, re-plot.

Or, alternatively:

Calculate the back-scattered spectrum for CO in the overtone region $4150\text{-}4350 \text{ cm}^{-1}$. Use bottom 25 km only, and include CO, H₂O, and CH₄, obtained from HITRAN on the web. CO profile can come from *B&S* Appendix D or another source (*e.g.*, GEOS-Chem modelers at Harvard). Use albedo = 0.1 (appropriate to land). Ignore Rayleigh scattering (why?) What spectral resolution appears to be necessary to successfully measure CO? What are the advantages and disadvantages of measuring the overtone versus the vibrational fundamental?

Intensities and widths in spectral line files given at 296 K. Approximate $Q(T)$ as $\propto T^1$ (linear molecules) or $\propto T^{1.5}$ (nonlinear molecules) in order to calculate $S(T)$ for each line in each layer.

Files:

brasseur-solomon-profiles.dat concentration profiles from *B&S*

oh-hitran.project OH line list extracted from HITRAN

hcl-hitran.project HCl line list extracted from HITRAN

o3bp.project Ozone cross sections with temperature dependence

voigt363.f90 Voigt subroutine subprogram

voigt363-function.f90 Voigt function subprogram

gauss.f90 alternate (to Voigt) Gaussian convolution for instrument width

hitran-molparam.txt HITRAN isotope codes and molecular weights